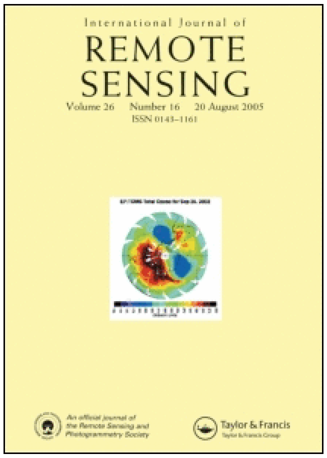

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Retrieval of atmospheric and oceanic properties from MERIS measurements: A new Case-2 water processor for BEAM

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A freely available data processor for the **B**asic **E**RS & ENVISAT (**A**)ATSR and **M**ERIS Toolbox (BEAM) was developed to retrieve atmospheric and oceanic properties above and of Case-2 waters from Medium Resolution Imaging Spectrometer (MERIS) Level1b data. The processor was especially designed for European coastal waters and uses MERIS Level1b Top-Of-Atmosphere (TOA) radiances to retrieve atmospherically corrected remote sensing reflectances at the Bottom-Of-Atmosphere (BOA), spectral aerosol optical thicknesses (AOT) and the concentration of three water constituents, namely chlorophyll-a (CHL), total suspended matter (TSM) and the absorption of yellow substance at 443 nm (YEL). The retrieval is based on four separate artificial neural networks which were trained on the basis of the results of extensive radiative transfer (RT) simulations by taking various atmospheric and oceanic conditions into account. The accuracy of the retrievals was acquired by comparisons with concurrent *in situ* ground measurements and was published in full detail elsewhere. For the remote sensing reflectance product a mean absolute percentage error (MAPE) of 18% was derived within the spectral range 412.5–708.75 nm while the accuracy of the AOT at 550 nm in terms of MAPE was calculated to be 40%. The accuracies for CHL, TSM and YEL were derived from match-up analysis with MAPEs of 50%, 60% and 71%, respectively.

1. Introduction

In December 2002, nine months after the successful launch of the Medium Resolution Imaging Spectrometer (MERIS) instrument on board of the European Space Agency (ESA) Environmental Satellite (ENVISAT) from Kourou in French Guiana, the **B**asic **E**RS & ENVISAT (**A**)ATSR and **M**ERIS Toolbox (BEAM) software project was released. The operating system independent BEAM software enables viewing and processing of ENVISAT MERIS, AATSR and ASAR data products (Fomferra and Brockmann 2005) and was developed by Brockmann Consult GmbH under contract to ESA. As an open source project BEAM allows for the integration of user developed scientific tools on the basis of plug-ins. This work describes the algorithms compiled into a BEAM Case-2 water plug-in with the aim to provide the users with information about its design and limitations. The integrated algorithms were developed by inverse modelling of radiative transfer (RT) calculations within a coupled ocean–atmosphere system by utilizing artificial neural network (ANN) techniques. Within this model-based approach, ANNs are

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well suited models to deal with the optical-complex Case-2 waters because multilayer feedforward networks with nonlinear transfer functions, as implemented in this work, are known as universal function approximators (Hornik *et al.* 1989). By utilizing an established and validated radiative transfer code as a forward model (Fischer and Grassl 1984; Fell and Fischer 2001), we generated a large data base of azimuthally resolved upward radiances in the MERIS channels at the Bottom-Of-Atmosphere (BOA) and at the Top-Of-Atmosphere (TOA) for a variety of Sun and observing geometries depending on the concentration of different types of atmospheric and oceanic constituents. The ANNs serving as inverse models were trained by the backpropagation algorithm (Werbos 1974) on the basis of randomly selected data subsets taken from the simulated data base.

2. Forward and inverse model parameterizations

The inputs to the forward model consist of several atmospheric and oceanic optical properties. In detail, the vertical profiles of temperature and pressure of an US Standard atmosphere (NOAA, NASA and USAF 1976) with a constant ozone loading of 344 Dobson units (DU) were used. The optical properties of aerosols entered the model through extinction coefficients and phase functions resulting from Mie calculations. We considered a mixture of maritime and continental aerosol models for the boundary layer and the troposphere according to Shettle and Fenn (1979) and the World Climate Research Program (WCRP 1986), while we assumed a constant background aerosol of sulphuric acid (H_2SO_4) aerosol in the stratosphere (WCRP 1986) with an aerosol optical thicknesses (AOT) of 0.005. The spectral aerosol extinction of the boundary layer and the troposphere was modelled by varying AOTs simulated in the range from 0.03 to 1. The underlying ocean model was characterized by varying concentrations of water constituents, namely chlorophyll-a (CHL), total (organic + inorganic) suspended matter (TSM) and yellow substance (YEL). Their concentration ranges covered in the simulations were 0.05–50 $mg\,m^{-3}$ for CHL, 0.05–50 $g\,m^{-3}$ for TSM and 0.005–1 m^{-1} (at 443 nm) for YEL, respectively. The inherent optical properties required as input to the RT simulations, such as the absorption and scattering coefficients of pure sea water, CHL, TSM and YEL were taken from published measurements or parameterizations. The total absorption of the sea water was modelled as a sum of the absorption coefficients of pure sea water itself, the absorption of organic particulate matter as a function of CHL, plus the absorption of inorganic particulate matter as a function of TSM and the absorption of YEL. The total scattering coefficient was modelled as a sum of pure sea water scattering and the scattering of total suspended matter. The absorption coefficient of pure water was taken from Pope and Fry (1997) and Hale and Querry (1973) while the pure sea water scattering coefficient was taken from Morel (1974). Further, the absorption of organic particulate matter was computed according to Bricaud *et al.* (1998) while the absorption of inorganic particulate matter was modelled according to a parameterization of Babin (2000). The yellow substance was assumed to be totally absorbing and was taken to be like the scattering coefficient of total suspended matter from Babin (2000). The scattering phase function of pure water was taken from Morel (1974). Moreover, a backscattering probability model of Case-2 waters from Zhang *et al.* (2002) was applied.

The inverse models are of fully connected feedforward networks with one hidden layer of neurons and were adapted during a supervised learning procedure based on a least-mean-squares approach: samples pulled randomly from the simulated data base were presented to the networks and their outputs compared against the expected outputs as given in the data base. The estimation error, i.e. the sum of squared differences between the network's outputs and the expected outputs, was used to adapt the parameters of the networks using the backpropagation algorithm. This has to be done sequentially for all data of the subsets until the total estimation error is minimal.

3. Processor architecture

The core of the processor consists of four ANNs. One network performs the atmospheric correction and derives reflectances at the BOA including the AOT at four wavelengths (440, 550, 670 and 870 nm), while the other three networks retrieve the concentrations of the above mentioned water constituents directly from the TOA measured radiances. The processor can be obtained from the official BEAM project web site (BEAM 2006) and is easily integrated into the BEAM environment (Fomferra and Brockmann 2005). It works within VISAT (the graphical interface) or in command line mode, useful for batch processing of larger numbers of data sets. Figure 1 shows the processing flowchart of the imbedded algorithms.

Once a MERIS Level1b file of interest has been selected, the processor can be launched (e.g. in graphic mode) within VISAT from the 'Tool' menu. A snapshot of the processor in operation is given by figure 2. After applying the Level1b Land, Bright pixel and Glint masks and converting the TOA radiances into reflectances a normalization to an ozone content of 344 DU is performed to be consistent with the simulation framework. After these preprocessing steps the input to all networks consists of the information of the TOA spectral reflectance (bands 1–7, 9–10 and 12–14) with additional information about the Sun and observer geometries, surface pressure and wind speed, on a pixel-by-pixel basis. During the retrieval each ANN input and output parameter is checked against its range of the simulated data subset used to adapt the inverse models and if out-of-range, an additional ANN flag is raised.

4. Results and conclusion

Here, the results of the algorithm validation are briefly summarized, which are described in detail in Schroeder (2005) and Schroeder *et al.* (2007).

The atmospheric correction stream of the processor was validated with concurrent ship-borne reflectance measurements of the North Sea turbid waters performed by the Institute of Coastal Research of GKSS, Geesthacht, Germany and of AOT data from the Aerosol Robotic Network (AERONET) station on Helgoland Island. The validation results can be summarized as follows: For the reflectance product a mean absolute percentage error (MAPE) of 18% for the spectral range 412.5–708.75 nm was derived while the MAPE of the AOT at 550 nm was found to be 40%. Compared to the standard MERIS Level2 reflectance product of the processor versions 3.55 and 4.06 the proposed algorithm reveals a significant increase in accuracy especially in the blue part of the spectrum, where the MERIS Level2 reflectances result in errors of up to 122% compared to only 19% with the proposed algorithm. A validation of the water retrieval algorithms was performed with concurrent *in situ* measurements taken in North and Baltic Sea waters, in the Gulf of Cadiz, close to Spain and in the Mediterranean close to the border of Israel. The

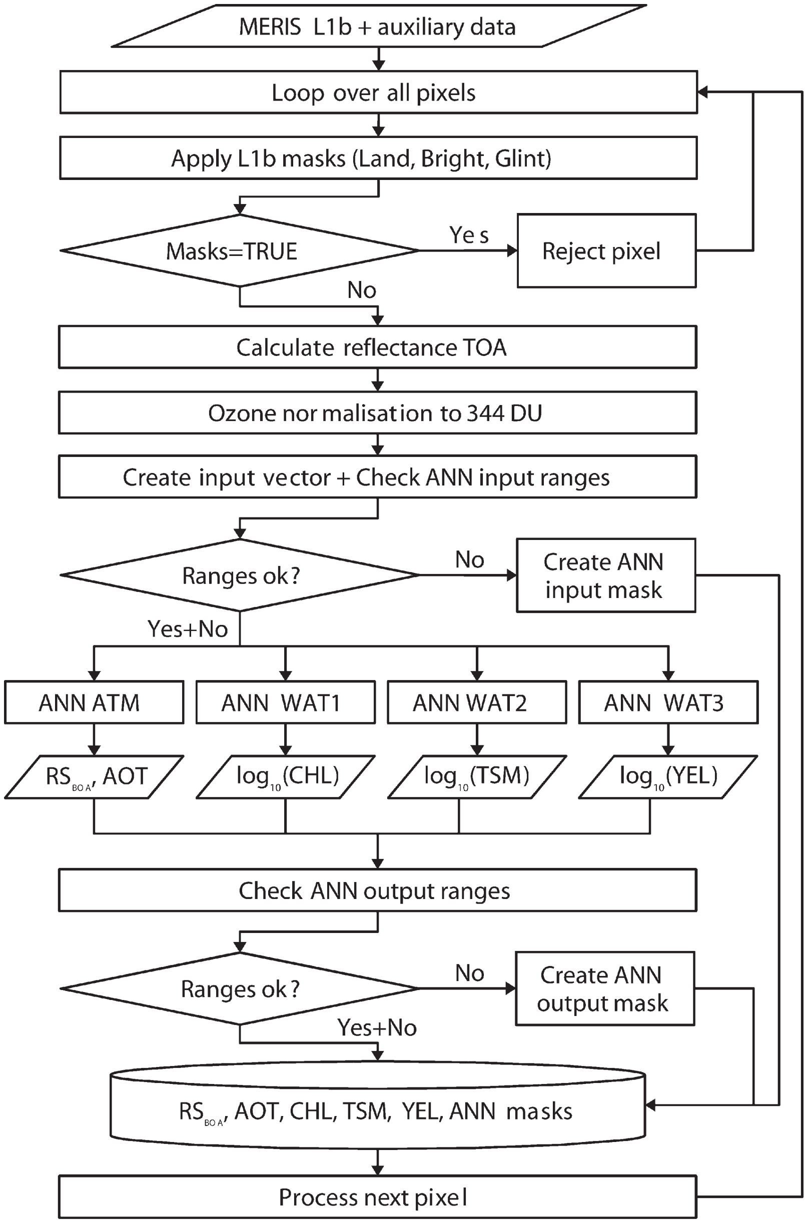

Figure 1. Flowchart of the proposed case-2 water processor.

findings here can be summarized as follows: For CHL an overall accuracy of 50% was derived through match-up analysis of 20 *in situ* samples covering a concentration range of 0.12–12.6 mg m^{-3}. For TSM a MAPE of 60% was acquired from 16 samples covering a concentration range of 2.71–14.3 g m^{-3}, while the accuracy of YEL was calculated to be 73% by match-up analysis of 13 samples with a concentration range of 0.38–0.94 m^{-1}.

Based on its bio-optical water model the processor is designed for European coastal waters but one of its strengths it is to produce accurate results within the

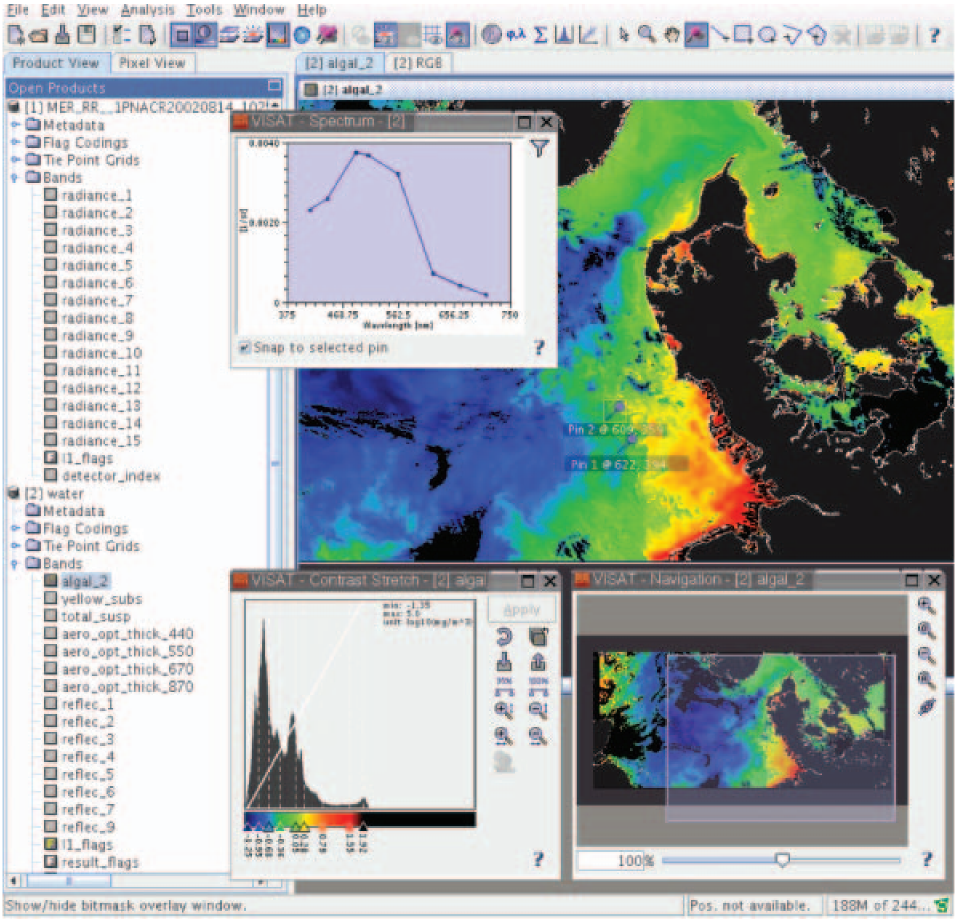

Figure 2. Snapshot of the BEAM environment with the proposed case-2 water processor in operation displaying retrieved chlorophyll-a concentrations for North Sea turbid waters. Available in colour online.

transition zone between coastal and open ocean waters. We do not recommend use of the water retrieval outputs for inland waters even though the atmospheric correction stream of the processor will produce reliable results for this application.

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